Can Immersive Virtual Environments make the difference in training industrial operators?

Salman Nazir¹, Annette Kluge², & Davide Manca¹

¹PSE-Lab, DCMIC “Giulio Natta”, Politecnico di Milano, Italy
²University of Duisburg-Essen, Duisburg, Germany

Abstract

The role of the operator’s performance for continuous, hazard-free and economically viable production in the chemical industry is of paramount importance. Even a minor error may result in a near miss, an abnormal situation, and even a catastrophic accident. This paper analyses and discusses the role played by distinct training methods performed in an Immersive Virtual Environment (IVE) to form and influence the performance of operators. An experiment was designed and conducted for a specific procedure of a polymerization plant, i.e. catalyst-injector switch, where the operator has to follow a sequence of actions. Two groups of participants (N = 24) were trained within the IVE according to different training methods. The Immersive Observers (IO) group observed a trainer explaining and performing the procedure, while the Immersive Actors (IA) group performed singularly and personally the procedure through a so-called guided-tour. The IO group showed higher accuracy, precision, process understanding, identification skill and lower help requirements than those of IA group, conversely IA group showed better speed when compared with the former. The results lead to the conclusion that IVE are not effective per se and need guidance by a competent trainer when the task is unfamiliar. The impact for future research and practice are discussed.

Introduction

Industry background

The contribution of chemical industry is enormous in terms of the quality of life that was achieved in recent past, the availability of goods, and reduction in costs of various necessary products, and optimization of energy consumption and production. Only in Europe, in 2011, the production of chemicals generated euro 539 billion in revenues. The chemical industry employed directly 1.1 million people working in a large number of companies (CEFEC, 2012). At the same time, each year millions of euros are lost in this sector because of accidents, unscheduled shutdowns or abnormal situations, for instance the notorious Deepwater Horizon oil spill caused an estimated economic loss of USD 90 billion. In terms of human lives, according to the International Labor Organization (2003), 2 million people are killed by their work every year, which means ca 5,500 people every day, ca 230 every hour and nearly 4 persons every single minute.
Most of the industrial accidents are triggered by some abnormal situation. An abnormal situation is referred to as a situation where the operating conditions deviate from the optimal range, which can result in the introduction of uncertainties to the system leading to forced shut-down of the plant or generating a serious accident scenario. Chemical processes run smoothly if operated within a safe region as shown in Figure 1. If the process falls outside that region, an abnormal situation occurs. If the abnormal situation is not managed properly, it can result in an accident.

\[ y \] vs. \( t \)

Figure 1. Qualitative trend of a chemical process variable, \( y \), as a function of time, \( t \). Since the process is intrinsically non-linear then the horizontal bands are usually not symmetric (PSE Lab, Politecnico di Milano).

**Influence of training on safety**

Most of the abnormal situations, which arose in a process plant, are less due to the failure of equipment, design or system and are more due to inappropriate reaction or understanding of the operator who transforms a possible little problem into a serious accident (Reinach & Viale, 2006). There are different stages before a major accident arises. Figure 2 shows the pyramid depicting different types of situations and incidents before the major accident takes place. Most of the situations including unsafe behaviours, near misses and minor incidents can be avoided if proper actions are taken in a timely and consistent way. If the situation can be controlled during the first three stages of the pyramid, then major incidents might be avoided.

In a recent study by Antonovsky et al. (2013) 45 petroleum industries were surveyed to understand the elements responsible for accidents using HFIT (Human Factor Investigation Tool). It was found that the most common reason among all failures was the wrong interpretation or assumption made by the operator. Therefore, the understanding, accuracy and errorless actions of operators are key elements in determining the safety and the continuous production from industrial plants. Various training methods are used in the industry with the aim of improving both operators’ understanding and performance.
use of immersive virtual environment for training industrial operators

**Figure 2. Safety pyramid reflecting different stages before reaching the major incident (PSE Lab, Politecnico di Milano).**

**Operator training**

An industrial operator is the person who works in the plant. Depending on his/her location and nature of job, s/he works either as Field Operator (FOP, working in field) or as Control Room operator (CROP, working in control room).

Although there is not a specific operators’ training method, nonetheless the concept of industrial training exists since decades (Kluge et al., 2009). Contrary to training methods for aviation industry, where homogeneity and consistency can be observed independent of the geographical and cultural differences, the process industry training methods face diversity and variance depending on country, nation, culture and stakeholder’s interest. Unfortunately, the value and impact of training has not been fully understood and appreciated in case of process industry. This study does not focus on the importance of training, which is already extensively covered by Nazir et al. (2012), Manca et al. (2013), Salas et al. (2013), and Kluge (in press).

The Authors have been working on advancement in training methods for industrial operators in order to improve their performance, reliability and ability to handle normal situation, abnormal situation and rare situations like start up or shut downs (Kluge, in press, Kluge et al., 2009, Manca et al., 2013, Nazir et al., 2013). Start-ups and shut downs are not the only rare events which take place in chemical plants, but other events like regeneration of some specific components at a periodic frequency are common events in industrial processes. The probability of running into an error in these rare events is higher as there is always a rather long time interval (usually and at least from 1 to 2 months) between consecutive events.

It has been shown that skilled performance can be directly co-related to quality and quantity of training (Kluge (in press), Proctor & Dutta 1995, Colquitt et al., 2000) and expertise (Ericsson et al., 1993). Burkolter et al. (2009) and Nazir et al. (2013) discussed the possible improvements in process control tasks attainable by different
training methods. Most of the conventional tasks are performed in the field and not in the control room, where automation, graphical data, numerical values are explicitly displayed on the screens of the DCS (i.e. Distributed Control System) solution. Simple skills like identification, attention management, following a sequence of actions in a precise and timely manner are sufficient to accomplish such tasks successfully.

Training of CROPs is considered essential and vital in the world of process industry. Conversely, FOPs have been mostly neglected by the training programs of the Industry. As extensively discussed by the authors of this manuscript, the training tool for FOPs should be immersive and capable of reproducing the spatial layout of the plant. Manca et al. (2013) coined the term Plant Simulator (PS) to describe an advanced training tool that is centred on the trainee and addresses the most relevant human factors issues related to his/her formation and personal involvement. In less technical words, the PS is a training simulator using IVE augmented by computational software and algorithms to assess the performance in a systematic manner. As reported in Nazir et al. (2013), the understanding of the plant geometry and most relevant process operations was significantly improved with respect to the conventional methodologies adopted to train FOPs. The benefits and usefulness of IVE implemented in the PS training solution was tested and shown by Nazir et al. (2012) and Colombo et al. (2013). Those experiments simulated an accident event and compared two different training methods, i.e. PowerPoint presentation versus PS (IVE). Conversely, the present study emphasizes on deepening the use of IVE by analysing two training methods within the PS solution for normal operating conditions. In the study, a replica of catalyst injector switch was developed in the PS by following the real process parameters, geometry and constraints. Moreover, an algorithm for assessment of performance was developed and integrated.

The purpose of these experiments based on alternative training methods is reaching the best possible training practice for industrial operators so to mitigate the losses (in terms of finance and human lives) in the process industry. This paper represents a step towards filling the gap in the development of universally viable and consistent training methods. Specifically, two groups of trainees are trained by means of distinct methodologies inside the same training environment. The first group is trained in an IVE by an expert trainer. These trainees observe the specific procedure for catalyst injector switch (discussed later) and represent the immersive observers (IO) group. The second group is trained by directly performing the actions within an automatic guided tour. This is the immersive actors (IA) group. The performance assessment on both groups of trainees allowed extracting the following bits of information:

1) Observing the trainer performing the actions in an IVE improves the performance in terms of accuracy, number of helps required and precision.
2) Performing directly the actions in an IVE (without the previous example of the trainer) improves response speed at the cost of accuracy.

**Methodology**

*Participants*
A total of 24 university students (12 Males; age 22-24 year; mean 20.8 year; SD 0.94 year) participated to the experiment. The participants were from the third year of the bachelor degree in Chemical Engineering at Politecnico di Milano. They applied to an open and free call. No economic reward was provided. In advance, the participants were asked about any previous experience on similar experiments and their interest in 3D gaming to increase a priori the groups formation and equalize and balance the experiment. The experiment was performed in accordance to the ethical standards laid down in the 1991 Declaration of Helsinki. All participants signed a consensus form prior to their participation to the experiment and were informed of the freedom of leaving the experiment without any prior notice. Participants were randomly divided into two groups of 12 people each, equalized for gender and previous experience (if any). Each participant was assigned an ID from 1 to 24. The immersive observers (IO) group was given the IDs from 1 to 12 while immersive actors (IA) group received IDs from 13 to 24. All the participants were amateurs, as they had not any experience of working in industrial plants.

Experimental setup

The catalyst injector switch

The training task consists in switching the operation of two catalyst injectors. This is a periodic but not routine task. The Spheripol process, where the catalyst-injector switch occurs, is the most widely used process for the production of polypropylene (PP), with a total production of almost 80 million metric tons per year (Spaniol et al., 2008). The necessary steps of switching the catalyst at the plant are performed periodically every 2 months. The technical details of this process and the catalyst switch mechanism are out of scope of this paper and can be found in the literature (Urdampilleta et al., 2006, Shi, et al., 2010). The procedure for catalyst injector switch involves a total of 29 actions. A successful catalyst switch can be ensured only by following accurately such a sequence. Any errors in following the sequence can result in triggering an abnormal situation that may lead to a significant impact on the process operation, thereby, resulting in huge economic losses. Failure of catalyst switch is enough to bring losses of millions of euros as it requires complex maintenance activities based on the shutdown of the plant (and following start up when the malfunction is fixed) with consequent production losses and need for production rescheduling. Therefore, other than analysing the effect of training methods in IVEs on the performance of operators, this study focuses the attention on the effectiveness of training procedures for catalyst-injectors switch in the production of PP.

During the development of the 3D model for catalyst-injectors switch, the details of the real process, in terms of geometry, process dynamics, physical appearance, valves locations and functions, and piping, were considered (see Figure 3).
Training

Pre-training

The participant (playing the role of FOP) experiences the PS as a 3D immersive environment (facilitated by 3D passive glasses) in a dark room with spatial sounds. The pre-training session is focused on the use of nun-chuck to all participants at the same time (see Figure 4a and 4b). Nun-chuck is the means of interacting with the IVE for current experimental setup. It allows moving around the process section where the catalyst injectors switch occurs.

Both groups were pre-trained for use of the nun-chuck. At this stage, participants had no prior knowledge about the function or significance of any valves and their location.
Training

In order to keep the time interval between training and performance assessment consistent, the IO group was trained and assessed in the morning and the IA group in afternoon of the same day. The pre-training session lasted the same for both groups.

IO the immersive observers group

The IO group was given a lecture using slides presentation, which consist of background information regarding the process, its significance. The sequence of the first 9 out of 29 actions (see above), which the participants will be performing, was also revealed in the last slide of the presentation (see Figure 5a). Both the training and assessment sessions limited the sequence to 9 out of 29 actions based on the available training time with relation to the capacity of working memory in the range of 7±2 chunks (Miller, 1956). At the end of the slides presentation, the IO group went to the 3D room (where the PS is installed). A trainer performed the 9 actions of the training procedure by means of the PS and the participants observed his actions. While performing the catalyst-injectors switch procedure, the trainer explained briefly the meaning of each action to disclose the not overt aspects of the task. The actions were performed at a slower pace than normal. Actually, the trainer took about 20 min instead of the usual 6 to 8 min in real operating conditions, so that participants could understand better the sequence and its meaning. All the participants were completely involved and immersed in observing and understanding the training session by wearing 3D glasses (see Figure 5b). The following step consisted in assessing the participants when performing the 9 actions individually. It was made sure that the discussions among participants, regarding the sequence and experiment, were avoided during the waiting time. Moreover, once a participant finalized the assessment procedure, s/he was suggested to leave the premises of the experiment.

IA the immersive actors group

In case of the IA group, the participants got a flavor of the experiment nature by means of a short oral introduction (without slides) that lasted 4-5 minutes and was
followed by the training on how to use the nun-chuck (see above). Later, each participant was taken to the 3D room (PS) for the individual training session without the trainer support. The automated guided tour took the participant through the 9 actions by following a yellow coloured visual cue (Figure 6). Once a step was performed, e.g. the valve was either opened or closed, the yellow border surrounding the specific piece of equipment changed into green to produce a positive feedback about the action correctness. After training half of the participants, they were called for the performance assessment session individually so to keep some consistency with the IO group as far as the time interval between training and assessment is concerned. The same pattern was used also for the remaining half of the participants of the IA group to keep the time interval between training and assessment consistent.

![Figure 6. A Participant of the IA group involved in the training session by the fully automated guided-tour procedure.](image)

The total time of training for the IO group was 40 minutes (15 minutes for slide presentation and 25 minutes for immersive training by the trainer), whereas each participant of the IA group took about 30 minutes for training.

Additionally, participants of both groups were informed about the procedure about how to request help. The help support was designed to avoid distraction during the performance assessment session. The help could be invoked by just raising one hand, which was read by a skeletal recognition algorithm based on the input from the Kinect device of Microsoft. Once the participant asked for help (during the assessment procedure) the following device to be operated in the actions sequence was highlighted in yellow. By doing so, the participant was able to continue the performance session without being stuck in the IVE.

**Performance assessment**

The operator/participant performance assessment is based on a hierarchical and computerized methodology that allows evaluating the effectiveness of a specific training method (Manca et al., 2012). Each action performed by the trainee during the assessment procedure is recorded and analysed. The assessment procedure is implemented in a computer program capable of evaluating not only the marks about the performance of operators but also registering, storing, and analysing the actions and decisions taken by the operator during the experiment with the help of a dedicated algorithm that runs in real time (Manca et al., 2012; Nazir et al., 2012).
With reference to the catalyst injectors switch procedure, the performance assessment is based on the following dependent variables, which are named as Operator Performance Indicators (OPIs) (see also Figure 7):

**Overall mark:** The total mark obtained by the trainee. It is evaluated by a dedicated algorithm and is based on the number and nature of errors conducted and the number of helps requested. In the experiment (based on the first nine actions out of the 29 total ones), the maximum obtainable (i.e. theoretical) overall mark was 30.04.

**Number of helps requested:** If and when the help(s) was requested by participants during the course of experiment; they were recorded by the assessment software. The possible range of score from helps requested can be from 0 to 9.

**Number of errors:** Each time the participant failed to perform the correct action the software registered it as an error. The total number of errors performed and their relative significance produce the most important contribute to the overall mark.

**Total time taken:** This OPI reflects the time taken by each participant to finalize the nine actions. The time taken in requesting and using the help contributed to the total time taken.

![Figure 7 Operator performance indicators for catalyst injectors switch procedure.](image)

### Results

#### Overall marks

As shown in Figure 8, nine out of 12 (75%) participants of the IO group obtained the maximum overall mark (which means they did not make any errors and did not ask for any help and took a time to perform the nine actions below a suitable threshold), whereas only 4 out of 12 (33%) participants of the IA group were able to achieve the same optimal result. Moreover, the lowest score among the IO group is for participant 5 i.e. 16.55, while for the IA group participants 18, 19, and 24 obtained
even lower scores. The overall marks for the participants of both the IO and the IA groups are shown in Figure 8.

With respect to our assumptions concerning the benefits of the IO training, these numbers reflect the better performance (in terms of overall marks) for the participants of the IO group when compared with that of the IA group, which is in accordance with the expectations of this study.

![Figure 8. Overall marks obtained by each participant (IO group: 1 – 12, IA group: 13 -24). Higher is better.](image)

**Number of helps requested**

In case of the IO group, only 3 participants (25%) needed any help for the completion of all the 9 steps. In case of the IA group there were 7 participants who asked for helps. Moreover, a deeper look into the data reveals that only one participant of the IO group requested help more than once (i.e. participant number 12 asked help 4 times). Conversely, four participants of the IA group requested more helps i.e. participants 17, 18, 19, and 24 requested helps 2, 2, 8, and 4 times respectively (see Figure 9).

![Figure 9. Number of helps requested by each participant (IO group: 1-12, IA group: 13-24). Lower is better](image)
The total number of helps asked by the IO group was 6 as compared to 19 in case of the IA group. This shows that on average group IA required about 3 times more helps than the IO group to finalize the sequence of actions. This means that our assumption concerning the advantage of the IO training and its impact on the helps requested is confirmed.

**Number of errors**

Number of errors made by the IO group was 3.5 times less than those made by IA group; the IO group outperformed the IA group also in terms of error-free procedures. As a matter of facts, there were 9 participants of the IO group and only 4 participants of the IA group who did not make any errors during the assessment procedure.

![Figure 10. Number of errors made by each participant (IO group: 1 – 12, IA group: 13 -24, (lower is better)).](image)

**Total time taken**

The last OPI calculated is the total time taken by each participant to finalize the experiment based on the 9 actions. The average time spent by the participants of the IO group was 407 s, that is 99 s higher than that of the IA group. Therefore, as per the assumptions of the study, the responsiveness and promptness of the IA group were higher than the ones of the IO group.

In summary, the IO group did perform better in accuracy and precision by running into fewer errors, whereas the IA group was faster in completing the same task but with a lower accuracy.
Discussion

This study has examined the impact of training methods, within an immersive virtual environment, on the performance of operators during a specific operating procedure. The overall mark reflects the accuracy with which the actions were performed. Moreover, it incorporates the number of helps requested and the relative significance of errors made. The IO group was more accurate and precise as was demonstrated by the individual overall marks. Therefore, the first assumption is correct and supports the earlier work (Nazir et al., 2013).

As mentioned in the results section, the number of helps requested by the IO group was far below the number of helps requested by IA group. The participants of the IO group probably developed a more accurate association for identifying the valves/devices and memorizing their location. They were supported in understanding the whole picture of the procedure and set of actions by observing the trainer and listening to his explanations. Similar reasons can be attributed to the number of errors made by the participants of each group. It is interesting to observe that 9 participants of the IO group did not make any error in identifying and operating the valves/devices. From a practical perspective, this is an important finding because during sensitive operations like catalyst-injectors switch, there is no space for any errors. One error in the sequence of valves/devices to be operated can lead to the emergency shutdown of the whole process. In case of error in the procedure sequence, the risk of undesired polymerization reactions inside the pipes (instead of the reactor) is rather high. When this happens, the whole plant must be shut down and the involved pipes and injectors must be maintained.

According to the authors’ impression even if IA participants spent efforts and attention in following the colours to perform the sequence of actions they were probably distracted from focusing on the complete sequence, the location, and the arrangements of valves/devices in the IVE because a clear explanation of the meaning of the sequence was missing and learning was bottom-up. In contrast the IO group received a further explanation of the sequence meaning and reason. Therefore, the IO group was supported in memorizing, understanding, and following the sequence by observing the expert trainer performing the actions.

The total time taken for each participant of the IO group was higher than that of the IA group. Actually, the participants of the IA group performed all actions during their training by following the colours. Nevertheless, due to the lack of an extended view of the scenario, the precision and accuracy in following the sequence of actions were not comparable to the ones shown by the IO group (see Figure 10).

It is worth adding a further comment, which is based on the efficacy of training in IVEs. When the authors designed the experiment, there were vivid discussions about the possibility by participants to perform the whole sequence of actions without doing any errors. The overall task looked, at least theoretically, extremely challenging and complex. Actually, some authors were supposing the task almost impossible due to the difficulty of remembering a rather complex sequence of nine actions applied to valves and devices that are very similar and occupying a reduced volume (see Figure 3). The scepticism was finally washed away since there were a
use of immersive virtual environment for training industrial operators

A good number of participants (from both groups) who were able to achieve the maximum overall mark corresponding to an error-free sequence of actions. It is rather surprising thinking at how an immersive virtual environment can train in a short time (30-40 min) a trainee to perform a complex sequence of actions with a quite good efficiency. IVEs implemented within a PS show their efficacy as tools to improve the training of FOPs in complex environments.

The authors are aware of the fact that this study has limitations, e.g., that the participants were all students and not “real” operators. Students are more accustomed to receiving information in the form of lessons than that of being exposed to a new environment. This means that the results cannot be easily generalized to plant operators with a different educational background and learning capabilities. It can be assumed that operators are of a different age and differently educated than the participants involved in this study. It would be necessary to conduct similar studies with real operators and analyse their performance to draw valid conclusions for organizational applications.

Conclusions and future work

This paper proposed a comparison of two distinct training methods implemented in an IVE to understand and analyse their influence on the performance of operators based on the accuracy and speed reflected by proper OPIs. It was found that observing a trainer when s/he is completely immersed in the 3D plant with spatial sounds resulted in improved precision and performance as compared to the training method when the trainee follows the procedure and set of actions (once) in the same IVE by means of a fully automated guided tour. Conversely, the response time achieved by latter training method was better than the former one. This study reinforced the previous work (Manca et al., 2013, Nazir et al., 2013, Kluge, in press) that maintain that a PS improves performance of operators when they are facilitated by an expert trainer and opens the way to find more suitable methods to exploit IVE training applied to the process industry. Improved performance of operators results in averting emergency shutdowns, abnormal situations, and accidents, thereby, saving financial and human resources.

From a practical perspective, catalyst injectors switch takes place on average every two months in several plants around the globe. The operator must follow a well-defined sequence of actions. The impact of each action brings to different results in terms of its significance with respect to the process. Similarly, the error made among the sequence of actions is a function of its relative significance and impact on the overall process. Missing one action or doing an error, e.g., opening a valve and allowing flowing water or oil instead of catalyst has a completely different impact if the opposite action is made. Both errors are apparently similar i.e. operating a wrong valve, however, the damage in terms of cost and possible injuries associated can be quite different. This task is independent of teamwork; therefore, the FOP is responsible to carefully perform all the actions in a precise manner that requires cognitive skills like perceptual and spatial memory, attention management, responsiveness and self-reliance and should be well trained.
The use of IVE in training industrial operators is a relatively new concept. This study shows its advantages and paves the way to several questions which require further research and investigations, e.g., how much background knowledge of the process is necessary before IVE training? How many times the trainee should practice in the PS/IVE before being certified to work on a real plant? What is the most optimal way of interacting with IVEs during training session? Further investigations are necessary to find the most suitable training method within immersive environments and to find answers to the questions reported above.

References


